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Sustainability and Environmentally Friendly Methods to Travel Over Waterways

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Honors Research Project

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Overall Summary

There are many methods of transportation that incorporate different forms of roadway construction. Throughout daily traveling, the main structures used are bridges and tunnels. Bridges are used as overpasses over valleys, canyons, and areas that require a large amount of dirt fill to bring the roadway up to the proper grade. Tunnels are underpasses through mountains, under city limits and waterways. Over the course of this article, different methods of bridging over water and tunneling will be discussed in detail to allow all readers to grasp how different methods affect the environment and the monetary impact. With the ever-changing climate and increased movement towards environmentally friendly materials and travel methods, this will be one of the key aspects discussed. On the other hand, it is necessary to determine the cost of more environmentally friendly transportation methods since each state and city is only given a set amount of money to spend on infrastructure. The overall purpose of this research is to determine if tunneling under or building a bridge over a waterway is more beneficial financially, environmentally, and is the better decision from an engineering design aspect when it comes to the construction and maintenance for each structure.

Construction Funding

In order to understand why the fiscal impact is a key component, it is beneficial to understand how funding works for construction jobs. Every state abides by different revenue fees for fuel and the same federal rate per gallon of gasoline and diesel. In the state of Ohio, “the largest source of revenue is the state motor fuel tax which is 38.5 cents for each gallon of gasoline and 47 cents for diesel fuel sold in the state” (Transportation.Ohio, 2021). On the other hand, in Missouri “the state fuel tax rate of 17 cents” (Transportation.Missouri, 2021) is applied to diesel as well as standard gasoline. All states require drivers to pay a vehicle registration and licensing fee based on vehicle type and classification. On the federal level, the motor fuel tax ranges from "18.4 cents per gallon for gasoline and 24.4 cents per gallon for diesel" (Transportation.Ohio, 2021) and funding also comes from tire, heavy truck, and trailer sales which are distributed to states through transportation funding acts. Through these funding avenues, states are able to allocate money towards different construction projects determined through inspections. Government engineers inspect and determine roadways that will require full depth or partial depth repairs and if bridges will be completely demolished or can withstand further elemental damages with only a repair job.

Methods of Bridge and Tunnel Construction

For bridge construction over a waterway, there are different methods that can be used depending on the area, water level, access, and soil conditions under the water. All types of bridges can be suspended over waterways such as beam, truss, arch, suspensions, cantilever, and cable-stay bridge forms. In order to understand the benefits and negatives of bridges, it is important to know the full construction process of bridges as shown in Figure 1.

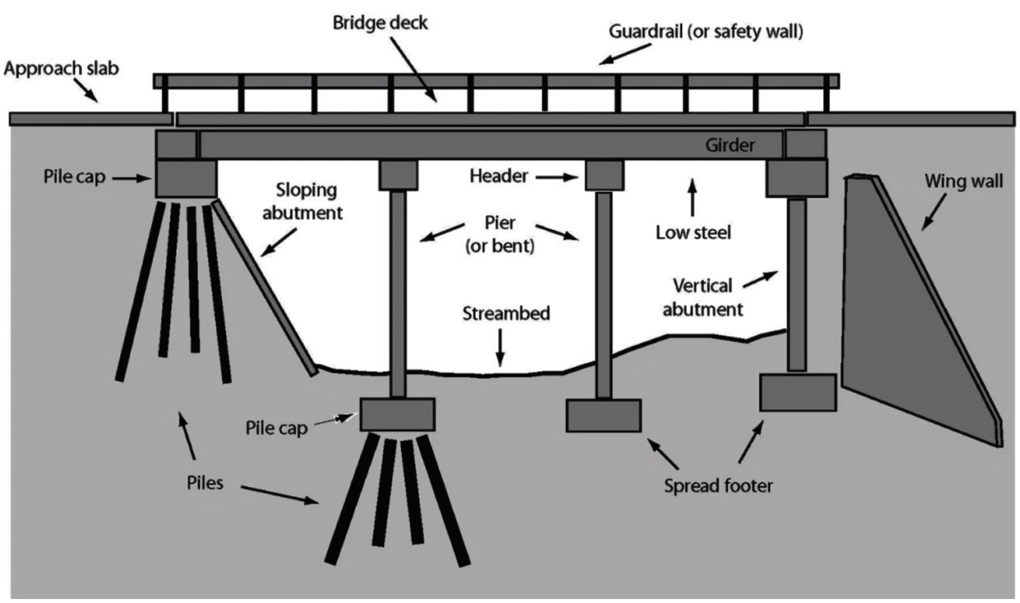

Figure 1: Substructure Diagram

The substructure of a bridge begins with determining the soil type for different styles of piling. The main piles used are wood, metal, and concrete encased which all require driving into the soil under the water. Once piles are driven, footers are formed and poured for the pier columns and abutments. After waiting for the concrete to cure, the pier and pier caps can be formed to allow for the superstructure to start to be constructed. The superstructure is built by erecting the steel beams, setting reinforcing rebar and pouring the concrete deck. Parapets are poured for driver safety along the edges of the bridge deck.

The hardest component to waterway bridge construction comes into play for the construction of the piles with which the piers will be poured onto. The main method to be discussed are cofferdams which is "a structure that retains water and allows a work area to be dewatered so that crews can pour concrete" (Dillon Hogan, 2018). There are differing types of cofferdams based on configurations, materials, and sizes, but the main focuses of this article are Braced, Cellular, and Portadam Systems. Braced Cofferdams, as shown in Figure 2, are made up of vertically driven single wall sheet piles braced on the inside of the box shaped cofferdam and water pumped from the inside (Dillon Hogan, 2018). Cellular Cofferdams are more extensive construction processes. They require driving sheet pile in circular patterns and repeating to form a series of circular cells to create a tight seal from water. These types of cofferdams are used for dam construction and dock facilities which require a larger area of land to be dewatered unlike a small perimeter needed for bridge piles. Lastly, Portadam Systems, as shown in Figure 2, are not driven into the ground, but instead are assembled and framed enclosed along the area for dewatering. Next a vinyl fabric membrane provides an impervious seal over the framing. With shallower waterways, Portadam Systems are preferred due to the little disturbance to soil under waterways and quicker installation.

Figure 2: Braced and Portadam Cofferdam

For tunnel construction, there are three main methods used which are immersed tubes, tunneling shields, and tunnel boring machines. To start constructing a tunnel, it is necessary to determine how deep the tunnel will be required since the majority of underwater tunnels are built under bed rock or dug into the firm soil to prevent flooding and collapse (Builderspace, 2021). Starting with immersed tube tunnel construction, some sections are built upon dry dock then taken into a trenched area to form the tunnel. This mitigates the need for compressed air required to keep the water from entering the tunnel during construction. The procedure involves building tunnel elements such as the outer steel shell are fabricated in ship lifts or yards then floated to sea to be positioned and filled with concrete. Before being submerged, bulkheads are fashioned to the tunnel ends to prevent water from entering then submerged into the dredged trench. The benefits of immersed tube construction is the lower cost of materials, quicker schedule due to simultaneous tasks completed at the same time, and the ability to still use the waterway instead of closing down the passageway. The negative aspects are immersed tubing properly waterproofing joints and possible sabotage if not deep enough within the bed rock (Immersed Tube Method, 2010).

With the Shield Tunneling Method, there is a higher focus on mechanics. The technique includes the use of a protective metal cylinder and following mechanical supports with a rotating cutting head positioned at the start of the shield. The benefit of the shield is to provide support and stabilization to the surrounding soil which can reduce ground pressures that often times cause cave-ins (Trenchlesspedia, 2021). As for the rotating cutting head, this mechanism "advances the boring machine through the soil… until the tunnel can be lined with a stable support structure" (Trenchlesspedia, 2021). Throughout the process, the tunneling method uses slurry pipelines, rails for transporting the lining segments, soil removal systems, and control rooms. There are multiple benefits of Shield Tunneling since the beginning of this technique in 1825 with a rectangular tunnel then in 1840 with a circular tunnel (Trenchlesspedia, 2021). Maintaining a safe workspace and continuous production allows to construction to work at a quicker and steady pace.

The last technique for tunneling is Tunnel Boring Machines or moles. Similar to Shield Tunneling, TBM uses circular cross sections to bore through all types of soil in addition to bed rock. The biggest advantage to TBMs is the ability to bore at diameters ranging from one meter to 16 meters (RailSystem). Two different types of machines can be used for hard rock boring such as shielded or open-type TBM. Open type allows rock support behind the cutter head. The use of gripper shoes allows to machine to progress along the path of the tunnel. Shielded "erects concrete segments to support unstable tunnel walls behind the machine" (RailSystem) keeping thrust forces from impacting the surrounding walls. Tunnel Boring Machines mitigate the use of lining the tunnel due to the smoothness of the tunnel wall. A major disadvantage to TBM technique is the expensive upfront cost of the machinery to mobilize onto the site and construction of the machine, though longer tunnels reduce the overall cost of the TBM due to the efficiency (RailSystem). Overall, the best method for boring underwater tunnels would be Shield

Tunneling method for larger length and diameter tunnels and immersed tubing method for shorter tunneling due to the constructability of the tunneling segments before submergence.

There are many uses for tunnels beyond general roadway traffic and pedestrian foot traffic. Using the train transportation system as an example, tunnels are used through mountain ranges in addition to under water ways. Similarly, subway systems travel through busier major cities underground. On a smaller level, tunnels have been built for wastewater, storm protection, and utilities in order to allow for no disturbance to normal daily activities. Being underground allows for easier travel as well as easier construction of tunnels.

Real Life Application

In order to grasp a better understanding of the difference between tunneling and bridge construction, it is important to compare similar sized structures to see where it made viable sense to choose tunneling or bridging. The two focuses will be the Holland Tunnel, in Figure 3, due to the new construction and the Bridge at Dingmans Ferry, in Figure 4, because of the span size and alterations made since its initial construction.

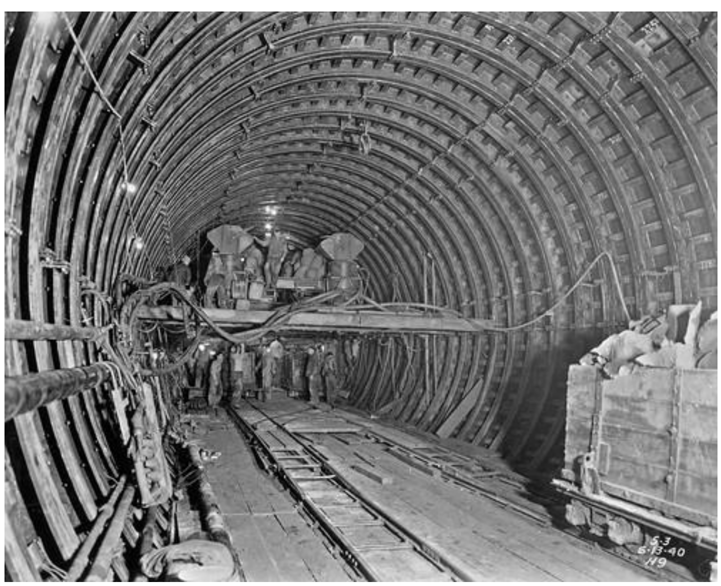

Figure 3: Holland Tunnel Construction

The construction of the Holland Tunnel began in 1920 after the New Jersey Interstate Bridge and Tunnel Commission and New York State Bridge and Tunnel Commission approved funds to connect both states under the Hudson River (Patrick Villanova, 2018). Over the course of the 18-month construction, pneumatically forcing cylindrical shields along the river bottom (Leonard Reed, 2022). The shields were shells made of iron rings filled with concrete behind the tunnel walls. The Holland Tunnel sits at 133 feet below sea level and spans 485 feet with a diameter of 22 to 25 feet including the five traffic lanes, median, and walking paths (Leonard Reed, 2022). During the construction of this 1.6-mile tunnel, a major concern was the ventilation system to remove the dangerous automobile fumes during the automobile age. Ole Singstad resolved the predicament with four ventilation buildings housing 84 fans which provide a change of air every 90 seconds establishing better air quality (Patrick Villanova, 2018).

Over the course of the tunnel's life, it has gone through multiple repairs, but will undergo a massive repair to correct the destruction Hurricane Sandy reaped on the Holland Tunnel. During the peak of the hurricane, the tunnel experienced 9 feet of flooding causing damages to lighting, pump room equipment, fire detection systems, power cables, and voice communication systems (Patrick Villanova, 2018). In addition to these repairs, the closure of the north tube will allow restorations to be made to the ceilings, concrete, wall tiles, curbs, and drum rings instead of pushing off these repairs to a later date. These restorations will cost the Port Authority $364 million with 84% reimbursement from federal funds (Patrick Villanova, 2018).

Figure 4: Dingman Bridge

Onto bridge construction, the main focus is the Dingmans Ferry bridge across the Delaware River. The reason it has kept the name Dingman Ferry is due to a ferry service run by Andrew Dingman between sawmills and grist mills along the Delaware River (DCDBC). The initial bridge structure was erected in 1836 as a wooden covered bridge, but was swiftly swept away with a flood in 1847 then re-erected and blown away by wind around 1855 (DCDBC). The general specifications of the structure are 547 feet long with 17.4 feet in width allowing for one lane of traffic crossing at a time. This road is toll collected and privately owner. Since 1900 the structure has gone through modifications and adjustments to increase safety and stay within newer bridge inspections and codes. There were three original truss spans erected in the 1900 manufactured by the Phoenix Iron Works. During the 1930's, guide rails provide protection to heavier loads on the original trusses. Every five to six years the wooden deck is recycled and the piers stemming into the river have been reinforced with concrete and steel.

Load Factor

A difference between tunnels and bridges are the loads taken into consideration for design components. Bridges carry around ten different loads that are taken into account. These loads are dead load or self-weight of the entire bridge, live load or moving load across the length of the bridge, impact loads or load of sudden vehicular movement, wind loads, longitudinal forces or braking and acceleration on the bridge, centrifugal forces or movement on a curvature, buoyancy effect, water current, thermal stresses, and seismic/earthquake loads (The Constructor, 2018). Traffic studies are also taken into consideration for types of vehicles such as length, weight, and model. On the other hand, tunnels carry gravity loads, rock loads which are applied when rock cover is necessary during the construction process, water pressure loads. Tunnels take into account underwater loads unlike bridges carrying loads caused by vehicles.

Environmental Impact

A key objective to determining the logical choice of structure is the environmental impact and the impact the environment takes on each structure. On the surface level, tunnels reduce noise congestion due to having traffic below sea level which is often times noisy and increase visual aesthetics as well as causing little to no disturbance to water life due to being under water. As mentioned previously, there is a high concern on vehicular emissions and pollutants through the tunnel. Though tunnels pose a major threat to local populations surrounding the entrance and exits, it is important to understand if this problem steams from tunnels themselves or rising population in major cities.

New Zealand's National Institute of Water and Atmospheric Research conducted a study on air quality in and around traffic tunnels focused on health impacts with a specific range of pollutants and recommendations for an approach at air quality management. The dependent variables to be discussed are the number of vehicles in the tunnel and the intensity and characteristics of vehicle emissions such as size, fuel type, speed, vehicle age, and engine specifications. There are three separate ventilation systems studied as possible design options: passive, longitudinal, and transverse. Passive ventilation includes piston effect which "requires no additional installations in the tunnel, making this the lowest cost option" (Australian Government, 2008). "Longitudinal ventilation refers to installations in which the piston effect is boosted by fans increasing ventilation" (Australian Government, 2008) and can be used in the forms of emergency smoke removal. As the most complicated and expensive ventilation, transverse requires a system to send fresh air and remove contaminated air along the length of the tunnel. In Figure 5, the illustration describes how airflows within the differing ventilation systems.

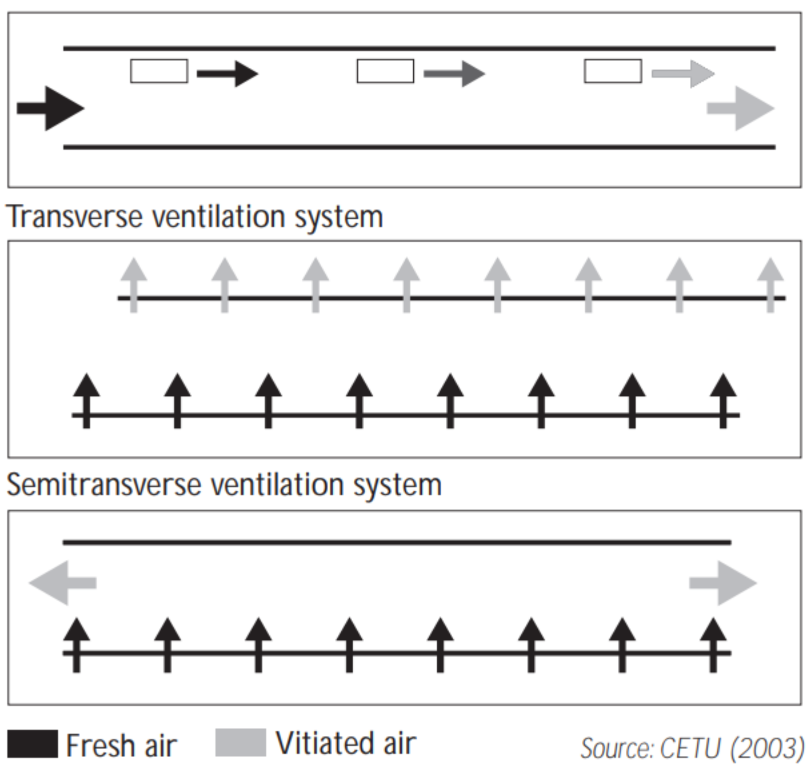

Figure 5: Ventilation Differentiation

In concluding evidence, the most effective management to air quality through and outside of tunnel access is vehicle emission reductions. Next, it was determined free-flowing tunnels are the least problematic in regard to health impacts and air quality in addition to being the most effective for transportation. On the topic of pollutant emissions, the New Zealand's National Institute of Water and Atmospheric Research found out "CO have fallen in the last two decades…emission factors for NO and PM10 have fallen less rapidly…these pollutants now constitute a larger proportion if tunnel air" (Australian Government, 2008). The overall recommendation provided in regard to emissions is monitoring concentration levels within the tunnel to determine the human exposure time to limit health implications. When designing a ventilation system for a tunnel, key components are the location of exhaust points and determining the rate of pollution generation and vehicle pollution production rates. Every tunnel has different needs and parameters for the location it is constructed, but these findings took into account different locations as well as lengths of tunnels to determine the best ventilation system to prevent long term health affects on those traveling within and around the tunnel.

In regards to bridge production, the biggest impact on the environment is the steel mining and milling productions as well as the high pollution emissions from heavy machinery such as cranes. In its most basic form, iron is a reaction between minerals to form ores such as Hematite and Magnetite nearest to the surface of the earth (GreenSpec). This resource is mined out of the earth to be sent to mills and manufactures. During the production of steel beams, raw materials and recycled materials are blasted with heat and oxygen to lower the carbon content in the naturally formed iron (GreenSpec). With all heating processes, there is a high concentration of carbon dioxide being released from the steel mills in addition to the hazardous runoff impacting all surrounding water ways and vegetation. One major byproduct of manufacturing is coke produced from the heating of coal which is then “removed from the oven and cooled before use in the blast furnace” (GreenSpec). Without proper filtration measures in place, coke breezes enter the water streams and pour into neighboring lands and water passages.

In addition to steel manufacturing, heavy highway machinery plays a large role in emissions into the atmosphere due to the use of diesel engines and high-powered equipment. Due to the multiple components of bridge construction, such as excavation, steel erection, and concrete pouring, different sizes and styles of equipment are used frequently. There was a study conducted by the UCSUSA in regard to overall health impact of construction machinery on the human population. For the pollutants in the air, “the five highest-polluting categories are responsible for 65 percent of PM and 60 percent of NOx emissions” (Don Anair, 2006). Figure 6 explains the difference in emissions based on the type of machinery from cranes to skid-steers. Diesel exhaust is among the most harmful particle within the atmosphere causing cancer, infertility, and long term adverse health effects. The best way to mitigate the impact of construction machinery emissions if through furthering technology away from diesel machinery and incentivizing cleaner construction equipment and procedures.

	Percent of Total PM from Construction Equipment	Percent of Total NOx from Construction Equipment	Useful Life (in years)
Excavators	17%	18%	17
Tractors/Loaders/Backhoes	16%	12%	18
Crawler Tractors (Tracked Bulldozers)	13%	13%	29
Rubber-Tired Loaders	12%	12%	21
Skid-Steer Loaders	7%	4%	13
Off-Highway Trucks	5%	9%	17
Rough-Terrain Forklifts	5%	3%	16
Graders	5%	5%	23
Off-Highway Tractors	4%	5%	31
Rollers	3%	3%	20
Trenchers	3%	2%	28
Scrapers	3%	4%	26
Cranes	3%	4%	19
Rubber-Tired Dozers	2%	2%	32
Pavers	2%	1%	26
Bore/Drill Rigs	1%	1%	10
Other Construction Equipment	0.4%	1%	16
Paving Equipment	0.3%	0.2%	24
Surfacing Equipment	0.04%	0.1%	22

Figure 6: Emission Over Equipment Lifetime

On the other hand, the environment affects bridge structures in a negative way due to the resisting forcing acting on the towering structure. Roaring waves and current, persistent winds, earthquakes, and water vessel collisions all must be taken into account when choosing the location and materials necessary for a bridge. A large concern for piers and piles is the drag forces created by water currents and results in scour holes. In the United States, 60% of bridge failures are caused by scour during water events (Lu Deng). In definition, scour holes are an erosive action that excavated material from the banks of streams and bedding under the piers and abutments in bridges. There has been a large push by the FHWA towards studying and predicting scour occurrence. “Radar is a system that uses electromagnetic waves to identify the range, altitude, direction, or speed of both moving and fixed objects” (Lu Deng) such as the motion of the current and stationary piers. One measure to mitigate the possibility of scours is by placing large amounts of rip rap around the foundation of piers.

It is impossible to account for a ship collision into a pier as shown in the collapse of the Sunshine Skyway Bridge in 1980. When considering ship collisions, engineers can design larger above water foundation to prevent ships for crashing directly into the piers, but this method can only be used for shallow waterways as shown in Figure 7. Deeper water requires “fender piles which are commonly connected by large ring beams” (The Constructor, 2017) that are distant from the pier to allow deflection as the rings consume the kinetic energy from striking ships.

Figure 7: Island Pier Foundation

Lastly, earthquakes are heightened in deeper water due to the combination of the load on the pier, the force exerted on the superstructure, and overturning moment along the base of the pier (The Constructor, 2017). “The eccentric load supported by the pier is crucially large in deep water which makes the selection of slender pier and massive base a desirable option” (The Constructor, 2017) such as circular columns. In addition to the superstructure being compromised, earthquakes cause erosion under the bedding of piers and can shift drive piles causing cracks and breakage in the concrete and structural columns. Ethically, civil engineers need to heavily consider the need for a bridge over fault lines and in high-risk earthquake locations due to likelihood of failure.

Conclusions

With all construction, many factors need to be taken into account when designing the structure necessary to solve the situation such as location, price, environmental influence, constructability, and design components. The benefits of bridge structures is the common knowledge of bridge systems and designing for expected failures due to past events. The biggest financial burden of bridges is the steel manufacturing and varying components necessary pump, drill, and drive piling under a bridge. Lastly, steel mills have a negative impact on the environment due to pollution and unregulated waste treatment as well as being influenced by the environment in a damaging manner that must be taken into consideration for design. Tunnels are an up-and-coming construction method used mainly in heavily populated cities to prevent above ground visual and physical constructs. There is a large push towards tunnel technology which is why shield tunneling has become the cheapest and most viable option. Financially, the equipment mobilization in and out of the job site is the highest cost since the majority of companies only rent equipment. As more research goes into tunneling, the issue of proper ventilation can be solved through air chambers and proper parameters for the potential of flooding and water corrosion.

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